VIOLENT SILICATE VOLCANISM ON IO IN 1996. J. A. Stansberry, J. R. Spencer, *Lowell Observatory, Flagstaff, Arizona, 86001, USA, stansber@lowell.edu*, R. R. Howell, *University of Wyoming, Laramie, Wyoming; currently at Lowell Observatory, Flagstaff, Arizona, 86001, USA*, C. Dumas, *University of Hawaii, Honolulu, Hawaii, 96822, USA*, D. Vakil, *University of Arizona, Tucson, Arizona, 85721, USA.*

Io's volcanic thermal emission is readily observed from both spacecraft and from Earth. Earth-based observations in Jupiter eclipse, at wavelengths of 2.2μm and longer, typically show color temperatures of $\leq$ 650 K (*e.g.*, Sinton *et al.* 1980; Spencer *et al.* 1992). Until recently higher temperatures, which are probably indicative of silicate volcanism, have only been reported during major 5-μm outbursts (*e.g.*, 1550 K in 1986, Veeder *et al.* 1994; and 1225 K in 1990, Blaney *et al.* 1995), though thermal emission seen in recent Galileo SSI and NIMS images requires temperatures above 700 (e.g., Belton *et al.* 1996). Our observing program extends to shorter wavelengths and has more frequent time sampling than previous groundbased work, and thus provides new information on the extent and temperature of high-temperature volcanism on Io.

We measured the 1.7 to 4.8μm brightness of the volcanic thermal emission from Io's Jupiter-facing hemisphere while Io was in Jupiter's shadow on approximately 56 nights during 1995 and 1996. The large number of observations (taken using NSFCAM at NASA's 3 meter Infrared Telescope Facility on Mauna Kea, Hawaii, and using the Ohio State Infrared Imaging Spectrometer at the Lowell Observatory 1.8 meter telescope near Flagstaff, Arizona) have allowed us to catalogue a number of volcanic eruptions, or ''events'', in which the in-eclipse brightness of Io increased significantly, and in some cases we have resolved or meaningfully constrained the brightness history of single eruptions. The positions and number of active volcanic centers on Io are constrained both by direct imaging of Io's disk (from IRTF where we often obtain 4 or more resolution elements across Io) and by using high-speed photometry obtained as Io is occulted by the limb of Jupiter (Spencer *et al.* 1990). The occultation lightcurves constrain the east-west location of eruptive centers to within about 100 km on Io.

Our observations also provide a measurement of the temperature of Io's volcanic thermal emission. At these relatively short infrared wavelengths we are sensitive to emission from the hottest components on the surface. We calculate the slope of the thermal emission using Io's in-eclipse brightness at 1.7 and 2.3μm and determine the color-temperature of Io at these wavelengths by finding the blackbody curve that gives the same 1.7 to 2.3μm slope. The $\sim 2\mu$m color-temperature is quite high, approximately 950 K, even when volcanic activity is at a minimum. During eruptions large enough to significantly influence Io's total brightness, the $\sim 2\mu$m color-temperature reaches values of 1100-1500 K. Temperatures this high clearly indicate the presence of refractory lavas on the surface, most plausibly silicates. The fact that the *minimum* $\sim 2\mu$m color-temperature we observed was near 950 K indicates that high temperature lavas are typically erupting somewhere on the surface, not only during bright events.

Two events in the fall of 1996 are of particular interest because the brightening in each instance appears to be due to a single eruption. Several other brightenings involve multiple eruptions at different sites, making the analysis more complex. The first event (hereafter ''9608A'') was observed on August 28 (10 days before the Galileo G2 encounter with Ganymede), and the second on October 6 of 1996 (hereafter ''9610A''). Event 9608A was relatively modest in strength, with the disk integrated flux at 2.3μm increasing by a factor of 7 over the baseline flux level seen 5 days earlier. The $\sim 2\mu$m color-temperature was 1100 K, and from the occultation lightcurve we know that this was the only large, high temperature eruption occurring on that date. We obtained further measurements on August 30, and September 6, 8 and 15 which show the event dimming monotonically until on September 8 the 2.3μm disk-integrated flux had returned to baseline levels. Based on resolved images of Io and the occultation lightcurve we place this event at an unnamed caldera at 15°W longitude, 2°N latitude. Keck telescope speckle images on September 6th (McIntosh *et al.* 1996) may provide a refined position estimate. Event 9610A was much larger: the 2.3μm flux increased by a factor of 60 over the baseline level observed 13 days previous. We next observed Io only two days later, and found that the flux had dropped by a factor of 30 from the peak level. The $\sim 2\mu$m color-temperature on September 6 was approximately 1500K. Again using both resolved images and the occultation lightcurve, we place this eruption at approximately 70°N, 30°W.

We are attempting to understand the volcanological implications of our observations using a thermophysical model of lava flows. The nature of the activity producing the thermal emission can be inferred from the shape of the observed spectrum. Numerical and analytical models of cooling silicate flows (Carr 1986; Howell 1997) show that when one introduces new material on the surface at a constant areal rate and allows that material to cool radiatively (either as an expanding flow or as an overturning lava lake) then one obtains a spectrum which can be characterized by only two parameters: the rate (R_A) at which new surface is generated, and the age (t) of the oldest material. For an expanding flow that t is the duration of activity. For an overturning lake that t is the overturn time. When a flow first begins the emission is dominated by the hot new surface. However because of the T^4 dependence of the power radiated, the surface cools quickly at first but then much more slowly. Therefore as t increases the spectrum broadens and shifts towards longer wavelengths until eventually at any given wavelength it reaches an "equilibrium" state where the intensity depends only upon R_A. In the following we use numerical models for cooling silicates to estimate R_A and t. We assume that the ''melting point'' of the material is 1400 K and adopt other physical constants appropriate for basalts.

The results of our modeling are reported in the table below. The quiescent (August 12, 1996) Io spectrum over the 3 to 5μm range can be modeled by silicate volcanism with the equilibrium $t = \infty$ case, with a certain amount of extra short t activity to raise the 1.7 and 2.3 micron points. (In the figure we simply model it using a combination of two blackbodies.) However spectra during events can only be modeled by activity characterized by extremely short t. For characteristic times (t) this short, the actual value of t and R_A are poorly determined, and only their product, the area of the active region, is well determined. We report that in terms of the radius of an equivalent size circle.

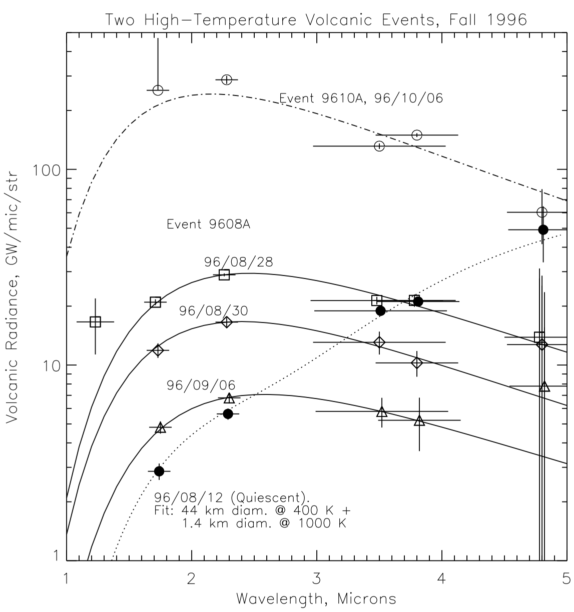

Figure 1. *Evolution of high-temperature volcanic events on Io. The quiescent flux on 96/08/12 is shown with filled circles and fitted by a two-component blackbody (dotted line), while the excess flux above this base level is shown for three dates during the 9608A event and for one date during the brighter 9610A event. For the 9608A event we obtain only upper limits on the excess 4.8-μm flux, because it is a small fraction of the quiescent value. For the 9610A event the detector saturated at 1.7 microns therefore we obtain only a lower limit. Also shown are the flow model fits to the event fluxes (solid and dot-dash lines): see Table 1 for parameters. For the most part the models work well, however our assumed melt temperature of 1400 K appears inadequate to fit the steep spectral slope of the 9610A event. The high 1.2-μm flux on 96/08/28 also suggests hotter material than is included in the model.*

Because the t for the active spectra are on the order of minutes or less yet we know the August event lasted at least 9 days, the activity cannot be modeled in turns of a spreading lava flow. If the new surface being exposed was not being eliminated on the few minute time scale indicated but was instead allowed to accumulate, then at the end of one week it would cover the area equivalent to a circle $\geq$60 km radius and would emit a 5-μm flux $\geq$50 times our upper limit. The extremely short value of t implies that we are either looking at a fire fountain or extremely vigorous overturning of the surface of a lava lake.

Date	t (s)	R_A (m^2s^{-1})	radius (km)
96/08/12	∞	224	
96/08/28	110	30200	1.03
96/08/30	73	22600	0.72
96/09/06	230	4520	0.58
96/10/06	$<$5	$>$2.7E6	2.09

The inability of even our $t = 5$ second model to produce the high spectral slope for the October event, and the excess emission apparently seen at 1.2μm during the first day of the 9608A event, suggests that our estimate of 1400 K for the temperature of the liquid may be too low. The high magma temperatures suggest the magma composition may be something more exotic than basalt: terrestrial komatiites might be one possible analog.

We believe that the rapid decline in the brightness of the 9610A event may be due in part to the viewing geometry. Because this event was near the north pole and was thus seen very obliquely, but was still very bright, it is a good candidate for a fire fountain, which due to its vertical extent would be prominent at high emission angles. A fire fountain could easily shut off in two days, as observed for 9610A. The oblique view could allow any lava flows generated by the event to be hidden from view by topography, explaining the lack of low-temperature emission. The 9608A event, in contrast, was viewed almost vertically, so any resulting lava flows could not be hidden by topography. A vigorously overturning lava lake, perhaps with fire fountain activity, is a likely explanation.

In conclusion, silicate volcanic activity (or at least, volcanic activity with magmas at silicate temperatures) is widespread and frequent on Io. Some silicate eruptions are so violent that their 1 to 5μm thermal emission is dominated by material at near-magmatic temperatures for periods of a week or longer, with little evidence for extensive formation of cooler crusts on the magma surface, or spreading lava flows. The sustained high temperatures of the 9508A event are apparently different from the more energetic January 1990 outburst, which cooled rapidly over three hours and showed evidence for extensive spreading and cooling lava flows (Davies 1996).

References

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